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13. ABSTRACT (Maximum 200 words)

Modeling methods applied in the field of turbulent combustion were investigated via Direct Numerical Simulations (DNS) and theoretical analysis with an emphasis on subgrid-scale modeling to be applied in Large Eddy Simulations (LES). The DNS results supported the conditional moment closure approximation, refuted the common modeling of differential diffusion effects, raised a suggestion for valid modeling of differential diffusion, resolved outstanding theoretical issues regarding mixing layers, and demonstrated the need for including flamelet/flamelet interactions in the modeling of extinction/reignition events. The DNS methodology was reconfirmed by comparison to the classical laboratory results of Comte-Bellot and Corrsin. A new subgrid-scale model (Large Eddy Laminar Flamelet; LELFM, a quasi-steady model) was established and applied to the prediction of laboratory results in a simulated mixing layer with nitric oxide/ozone reaction. The results support the modeling. New results were derived and confirmed via DNS regarding the the subgrid-scale modeling of the filtered mixture fraction, its second moment and dissipation rate.

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EVALUATION OF CLOSURE MODELS OF TURBULENT DIFFUSION FLAMES

(AFOSR Grant No. F49620-1-0092)

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DISCUSSION OF RESEARCH PROGRESS

(February 15, 1977- February 15, 2000)

This review is primarily based on papers that have been published in the archival literature.

Direct Numerical Simulation Investigations

Our group performed a systematic study of the applicability of the Conditional Moment Closure (CMC) approximation that has been introduced by Bilger (1993). The work started before the time period covered by this report with the investigations of Mell et al. (1994), who used a one-step chemistry approach, and Montgomery et al. (1993) who applied more realistic, hydrogen/oxygen chemistry. Both investigations considered incompressible flow conditions. The new work of Montgomery et al. (1997) presents three-dimensional direct numerical simulations of a seven-species, ten-reaction hydrogen-oxygen mechanism in decaying, variable density, isotropic turbulence.

An obvious limitation on the CMC approach is the influence of high activation energy on the negligibility of the conditional fluctuations. Accordingly, one of the focuses of Montgomery has been the investigation of the $\text{H} + \text{O}_2 \rightleftharpoons \text{OH} + \text{O}$ reaction. The detailed study has fully corroborated the validity of the CMC approach to predict the DNS data. The DNS data were also used to check the validity of the steady-state approximation to predict O and OH and to investigate the applicability the manifold-approach of Maas and Pope (1994).

Differential diffusion is due to differences in the molecular diffusivities of different species, momentum and heat. Of special interest to the modeling of hydrogen and hydrocarbon flames is the influence of the preferential diffusion of H_2 and H. We have investigated the problem of differential diffusion via DNS and theoretical derivations in two consecutive papers (Nilsen et al., 1997, 1999).

The first paper studies the influence of differential diffusion on mixing; the second paper uses the results of the investigation of mixing in reacting cases. The simulations show that the effects of differential diffusion disappear with increasing values of the Reynolds and Peclet numbers. This is in line with theoretical expectations and points to the erroneous nature of the modeling commonly used (Pitsch and Peters, 1998). It is shown furthermore that the clue to the modeling of the influence of differential diffusion is in the modeling of the conditional fluctuations. Whereas limitations on the resolution did not allow to investigate the modeling in detail, looking at our results in conjunction with similar results of Kröenburg and Bilger (1998), a two-step procedure can be established to predict differential diffusion effects, e.g., in a hydrogen-air flame. In the first step differential diffusion effects are neglected and the conditionally averaged specie mass fractions are computed. In the second step we use the conditional averages calculated in the first step and numerical constants determined from DNS to model the conditional averages in the equations of H_2 and H and solve the equations again. Since differential diffusion is related to the small scales whose dynamics is approximately universal, the parameter values obtained from DNS are expected to be applicable in both RANS and LES.

Recent (yet unpublished) DNS results investigate the influence of the local value of the scalar dissipation rate on the extinction-reignition of "flamelets". The results demonstrate that quasisteady-flamelet ideas can be used to predict extinction but are insufficient to describe the process of reignition. The reason for this is that present day flamelet modeling is based on the concept of independent "counterflow-flamelets", whereas reignition is most of the time not autoignition but is promoted by neighboring hot flamelets. We are presently in the process of generalizing the flamelet model by introducing interaction between the flamelets.

Subgrid-Scale Modeling

We have developed one of the first subgrid-scale models for (LELFM) use in large-eddy simulations of turbulent reacting flows (Cook and Riley, 1994, 1997; Cook, Riley and Kosaly, 1997). This model, utilizing flamelet concepts combined with some of the latest features of subgrid-scale modeling, addresses non-premixed, continuously burning reactions at somewhat high Damkohler numbers. It has relatively low computational overhead associated with the chemistry modeling, and can be applied to realistic thermo-chemistry, giving it a broad range of applicability. A number of researchers are now working on related subgrid-scale modeling approaches.

Our principal idea is to use the quasi-steady flamelet (LELFM) approximation in the subgrid-scale modeling of turbulent flames that are burning far from extinction. Cha and Kosaly (2000) published a new investigation of the validity condition of quasi-steady flamelet modeling. The condition given deviates from the condition commonly used (Peters, 1999). The new condition accounts for the somewhat counterintuitive finding that the quasi-steady approximation works better close to nozzle in a jet flame than close to the tip. (Note that, close to the tip, the approximation is not needed since the quasi-steady flamelet model can be replaced by the equilibrium chemistry approach.) The theoretical derivation is supplemented by computed (RANS) results referring to a hydrogen/air jet flame.

More recently we have been examining various assumptions in the subgrid model by comparisons of modeling predictions mainly with results from high resolution, direct numerical simulations. Specifically we have addressed the subgrid-scale modeling of the filtered mixture fraction, its second moment, and its dissipation rate (de Bruyn Kops et al., 1998), quantities which are called for in the subgrid-scale modeling procedure. To test the model further, we have recently performed very high resolution direct numerical simulations of the nitric oxide/ozone experiments of Bilger et al. (1991) (de Bruyn Kops, 1999; de Bruyn Kops and Riley, 2000b); the results are being used for further validation of the subgrid-scale model. The general result of our validation studies to date is that the model works very well for the range of problems that it was intended, i.e., continuous burning, non-premixed, somewhat high Damkohler number cases.

Considerable effort has been made in improving and expanding the methodology of direct numerical and large-eddy simulation of reacting flows, in order to utilize the simulations to better understand the combusting flows and also to test models for RANS and large-eddy simulations. With a detailed understanding of the methodology and the efficient use of DOD high performance computers, we were the first to perform accurate direct numerical simulations of the classic laboratory experiments of Comte-Bellot and Corrsin (1971) (de Bruyn Kops and Riley, 1998). This has been followed by the first accurate direct numerical simulations of turbulent scalar mixing layers, and the resolution of some outstanding theoretical issues related to mixing (de Bruyn Kops and Riley, 2000a). In both cases the agreement with the laboratory data was very good, giving confidence in the methodology. Accurate simulations of both of these cases were required in order to simulate the experiments of Bilger et al.,

which addressed the same flow and mixing configuration. Recently the direct numerical simulation methodology was extended to very accurate simulations of strongly temperature-dependent reactions (de Bruyn Kops, 1999; de Bruyn Kops and Riley, 2000), which is now being used in our studies of extinction and re-ignition. Finally, at the present we are developing the methodology for very accurate direct numerical and large-eddy simulations of reacting turbulent jets, both for model testing and for comparisons with laboratory data.

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Presentations

J. J. Riley. 1997. Invited presentation at the Workshop on Turbulent Transport and Modeling, Los Alamos National Laboratory, June.

J. J. Riley and A. W. Cook. 1997. Invited presentation at the conference Computing the Future II; Computational Fluid Dynamics and Transonic Flow, June. This paper was subsequently published as: Cook, A. W., and J. J. Riley. 1998. Progress in subgrid-scale combustion modeling, in *Computational Fluid Dynamics Review 1997*, M. Hafez, ed., Wiley.

J. J. Riley. 1997. Invited seminar at the Battelle Pacific Northwest National Laboratory, August.

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Nilsen, V. and Kosály, G., 1997 "Differentially Diffusing Scalars in DNS Turbulence," AIAA 35th Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 6-10, 1997, Paper No. 97-0256

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deBruynKops, S. M., Kosály, G., and Riley, J. J., 1997 "Large Eddy Simulations of Non-premixed Turbulent Reacting Flows," 50th Annual meeting of the DFD, APS, San Francisco, CA, November 23-25.

V. Nilsen, W. E. Mell, and G. Kosály, 1997 "On Reynolds Number Similarity in Turbulent Flows," 50th Annual meeting of the DFD, APS, San Francisco, CA, November 23-25.

J. J. Riley. 1998. Invited lectures at the Second ERCOFTAC Summer School, Stockholm, Sweden, June. These lectures were subsequently published as: Riley, J. J. 1999. *Turbulent Combustion Modeling, in Transition, Turbulence and Combustion Modeling*, A. Hanifi et al., eds., Kluwer.

J. J. Riley. 1998. Invited seminar at Lawrence Livermore National Laboratory, July.

J. J. Riley. 1998. Invited seminar at Stanford University, July.

J. J. Riley. 1998. Invited seminar at the Annual Meeting of the Mexican Physical Society, San Luis Petosi, Mexico, November.

G. Kosály: 1998. "Recent Developments in the Modeling of Diffusion Flames," Center for Turbulent Research, Stanford University Feb.~(1998)

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V.Nilsen and G.Kosály, 1998 "Differential diffusion in turbulent reacting flows," Third International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames, Boulder CO, July 30--Aug 1.

V. Nilsen and G. Kosály, 1998 "Differential Diffusion in Turbulent Reacting Flows," at American Physical Society Division of Fluid Mechanics Annual Meeting, Philadelphia, PA, 22-25 Nov.

J. J. Riley. 1999. Invited seminar at the California Institute of Technology, January.

J. J. Riley. 1999. Invited presentation at the Second AFOSR Conference on DNS and LES, Rutgers University, June.

S. M. de Bruyn Kops and J. J. Riley. 1999. Invited seminar at Lawrence Livermore National Laboratories, July.

J. J. Riley. 1999. Invited presentation at the Workshop on Turbulence Measurements for LES, sponsored by NSF, AFOSR, ONR, DARPA and DOE, October.

J. J. Riley and S. M. de Bruyn Kops. 1999. Presentation at the Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, New Orleans, November.

G.Kosály, 1999 "Quasi-Steady Approximation in Diffusion Flame Modeling" at University of California, San Diego, March.

G.Kosály, 1999 "Differential Diffusion in Reacting Flows" at Center For Turbulence Research, Stanford University, February.

PERSONNEL

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PhD students: S. M. deBruynKops (graduated in 1999), V. Nilsen (graduated in 1998), Y. Zhu (ongoing), P. Sripakagorn (ongoing). S. Mitarai (ongoing).

MSc students: D. Yong (Applied Math), C. Flynn (graduated in 1998).

SIGNIFICANT INTERACTIONS

J. J. Riley was co-organizer of the Workshop on Turbulence Measurements for LES, sponsored by NSF, AFOSR, ONR, DARPA and DOE, October, 1999. The report resulting from the workshop, co-authored by Riley, is available on the WWW at: <http://www.me.washington.edu/les/>.